

Modal Mapping Techniques for Geoacoustic Inversion and Source Localization in Laterally Varying, Shallow-Water Environments

George V. Frisk
Department of Ocean Engineering
Florida Atlantic University
SeaTech Campus
101 North Beach Road
Dania Beach, FL 33004
phone: (954) 924-7245 fax: (954) 924-7270 email: gfrisk@seatech.fau.edu

Grant Number: N00014-04-1-0296

LONG-TERM GOALS

The long-term goal of this research is to increase our understanding of shallow water acoustic propagation and its relationship to the three-dimensionally varying geoacoustic properties of the seabed.

OBJECTIVES

The scientific objectives of this research are: (1) to develop high-resolution methods for characterizing the spatial and temporal behavior of the normal mode field in shallow water; (2) to use this characterization as input data to inversion techniques for inferring the acoustic properties of the shallow-water waveguide; and (3) to use this characterization to improve our ability to localize and track sources.

APPROACH

An experimental technique is being developed for mapping the normal mode field and its wavenumber spectrum as a function of position in a complex, shallow-water waveguide environment whose acoustic properties vary in three spatial dimensions. By describing the spatially varying spectral content of the modal field, the method provides a direct measure of the propagation characteristics of the waveguide. The resulting modal maps can also be used as input data to inverse techniques for obtaining the laterally varying, acoustic properties of the waveguide. The experimental configuration consists of a moored, drifting, or towed source radiating one or more pure tones to a field of freely drifting buoys, each containing two hydrophones, GPS navigation, and radio telemetry, as shown in Fig. 1. A key component of this method is the establishment of a local differential GPS system between the ship and each buoy, thereby enabling the determination of the positions of the buoys relative to the ship with submeter accuracy. In this manner, the drifting buoys create 2-D synthetic aperture horizontal arrays along which the modal evolution of the waveguide can be observed in the spatial domain, or after beam forming, in the horizontal wavenumber domain. In this context, two-dimensional modal maps in range *and* azimuth, as well as three-dimensional bottom inversion in range, depth, *and* azimuth, become achievable goals. In addition, these high-resolution measurements have provided significant new insights into source localization and tracking techniques.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2008		2. REPORT TYPE Annual		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE Modal Mapping Techniques For Geoacoustic Inversion And Source Localization In Laterally Varying, Shallow-Water Environments				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Florida Atlantic University, Department of Ocean Engineering, SeaTech Campus, 101 North Beach Road, Dania Beach, FL, 33004				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES code 1 only					
14. ABSTRACT The long-term goal of this research is to increase our understanding of shallow water acoustic propagation and its relationship to the three-dimensionally varying geoacoustic properties of the seabed.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

WORK COMPLETED

Prior to 2006, three successful Modal Mapping Experiments (MOMAX) were completed. Two of these experiments (MOMAX I and SWAT/MOMAX III) were conducted in the East Coast STRATAFORM/SWARM area off the New Jersey coast and one (LWAD 99-1/MOMAX II) was carried out in the Gulf of Mexico. In these experiments, several drifting MOMAX buoys received signals out to ranges of 20 km from moored, drifting, and towed sources transmitting pure tones in the frequency range 20-475 Hz. In the traditional MOMAX deployment, a source transmits a pure tone (usually several) of precisely known frequency to the MOMAX buoys. The known carrier frequency contribution to the total phase is removed from the measured signal, and the resulting pressure field magnitude and phase versus time data are then merged with the corresponding GPS-derived source-receiver positions versus time. This procedure enables the determination of the pressure magnitude and phase as a function of two-dimensional position. High-resolution beam-forming techniques (corresponding to the application of an asymptotic Hankel transform) and inverse methods are then applied to these synthetic aperture data to obtain the modal information and the geoacoustic properties of the seabed.

On Aug. 30 – Sept. 5, 2006, MOMAX IV was successfully conducted as part of SW06, the ONR-sponsored, multi-institutional, multi-ship, series of shallow-water experiments that were conducted off the New Jersey coast throughout the summer of 2006. A wide range of environmental data was also obtained as part of SW06 that included an extensive suite of physical oceanographic measurements. As a result, a primary focus of SW06/MOMAX IV was the study of the effects of water column variability on the modal inversion process.

SW06/MOMAX IV was conducted aboard the R/V Oceanus, which served as the source ship from which the NUWC J15-3 sound source was suspended from the A-frame at a depth of 60 m. The source transmitted pure tones for a period of approximately 25 hours with frequencies of 50, 75, 125, and 175 Hz. These signals were received by 4 drifting MOMAX buoys, as well as an 8-channel Webb vertical line array (VLA), out to ranges of 10 km. The VLA, with 8 m hydrophone spacing, was deployed during MOMAX IV on Aug. 31 and recovered on Sept. 8 on a subsequent R/V Oceanus cruise.

The MOMAX buoy suspension system, including the locations of the two hydrophones at nominal depths of 40 m and 43 m, is presented in Fig. 2. Also shown is a temperature/pressure module which is mounted directly above the upper hydrophone. Both the VLA and the sound source string were also outfitted with a series of temperature sensors. The ship track, the trajectories of the drifting buoys, and the location of the VLA are illustrated in Fig. 3. Also shown are the positions of several environmental and source moorings that were already present as part of the suite of SW06 experimental assets.

RESULTS

Of particular interest is a physical oceanographic event that occurred on approximately day 247.6 and manifested itself as a significant fluctuation in the acoustic data. At that time, the temperature sensors in the area detected the passage of an internal wave, which is depicted as a thick blue line in Fig. 3. The speed and direction of this internal wave were determined to be 0.61 m/s and 319 degrees, respectively. Figure 4 shows that the corresponding variations in the acoustic pressure magnitude measured on Shemp are as high as 40 dB at 50 Hz. Because the acoustic records closely mimic the temperature measurements, the onshore progression of the internal wave can be tracked using either the temperature records or the acoustic data obtained on three MOMAX buoys, as shown in Fig. 5.

Furthermore, it is clear from Fig. 6 that the acoustic fluctuations also mimic the depth excursions of the upper hydrophone, as measured by the temperature/pressure module on each buoy. The possible physical mechanisms by which the internal wave activity may be causing these large acoustic fluctuations are currently under investigation. The nature of this effect is further elucidated by examining the acoustic spectrogram associated with the upper hydrophone data at Shemp. Here a broadband smearing effect is observed (cf. Fig. 7), suggesting that the physical mechanism may be due to: (1) a resonant propagation effect, (2) strumming, (3) flow noise, or (4) some other hydro-mechanical effect. Work is also continuing on inversion of the acoustic data for internal solitary wave properties and geoacoustic properties of the seabed.

IMPACT/APPLICATIONS

The experimental configuration consisting of a CW source and freely drifting buoys will provide a simple way to characterize a shallow water area and may be useful in survey operations. In addition, the planar, synthetic receiving array may offer an effective new technique for localizing and tracking sources of unknown, quasi-stable frequency in shallow water.

TRANSITIONS

The synthetic aperture technique and Hankel transform inversion methodology which underlie the modal mapping method have been implemented in the ACT II experiment, sponsored by DARPA and ONR, and have been used in the REMUS towed array experiments being conducted by Carey and Lynch. This approach has also been adopted by several research groups internationally, including the Japanese groups involved in SWAT. Transition opportunities are currently being pursued with NAVAIR and NAVCEANO.

RELATED PROJECTS

MOMAX I and III, as well as SW06, were conducted in the same area off the New Jersey coast where the ONR-sponsored STRATAFORM, SWARM, PRIMER, Geoclutter, and Boundary Characterization experiments were carried out. The extensive geophysical, seismic, acoustic, and oceanographic data obtained in this suite of experiments are being used to ground truth the MOMAX measurements.

The SW06/MOMAX IV data analysis and interpretation are being carried out in collaboration with a number of other SW06 investigators, including:

Acoustics: Kyle Becker, Ross Chapman, Harry DeFerrari, Bill Hodgkiss, David Knobles, Jim Lynch.

Geoacoustics: John Goff, Altan Turgut.

Physical Oceanography: Tim Duda, Glen Gawarkiewicz, Scott Glenn, Frank Henyey, Jim Moum, Jonathan Nash.

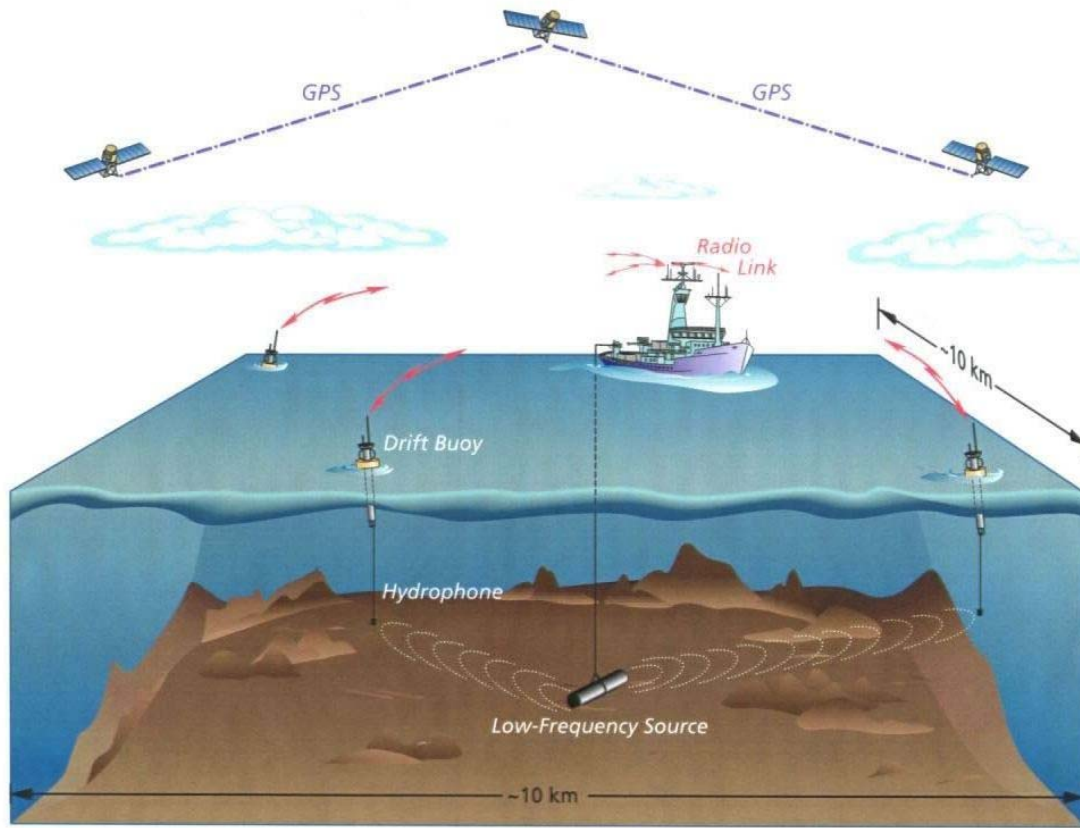
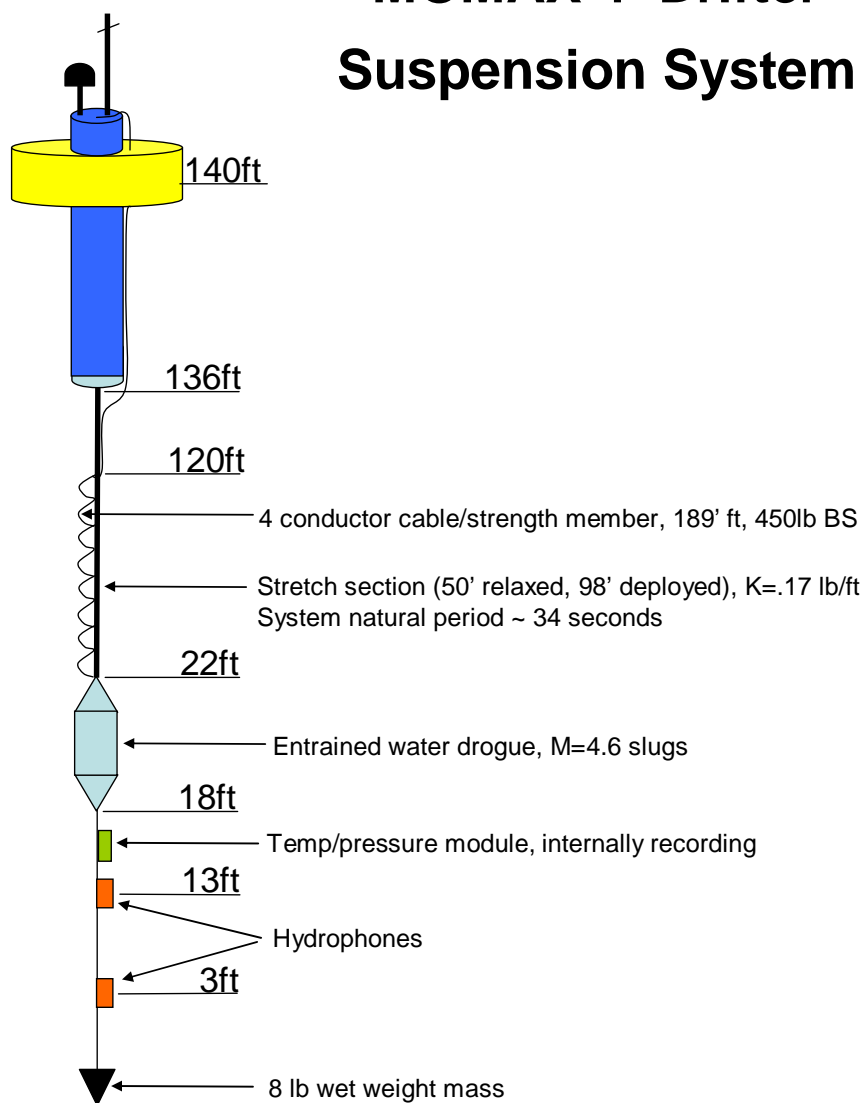


Figure 1: MOMAX experimental configuration.

MOMAX 4 Drifter Suspension System



vdH, 2006

Figure 2: MOMAX buoy suspension system with temperature/pressure sensors and 2 hydrophones.

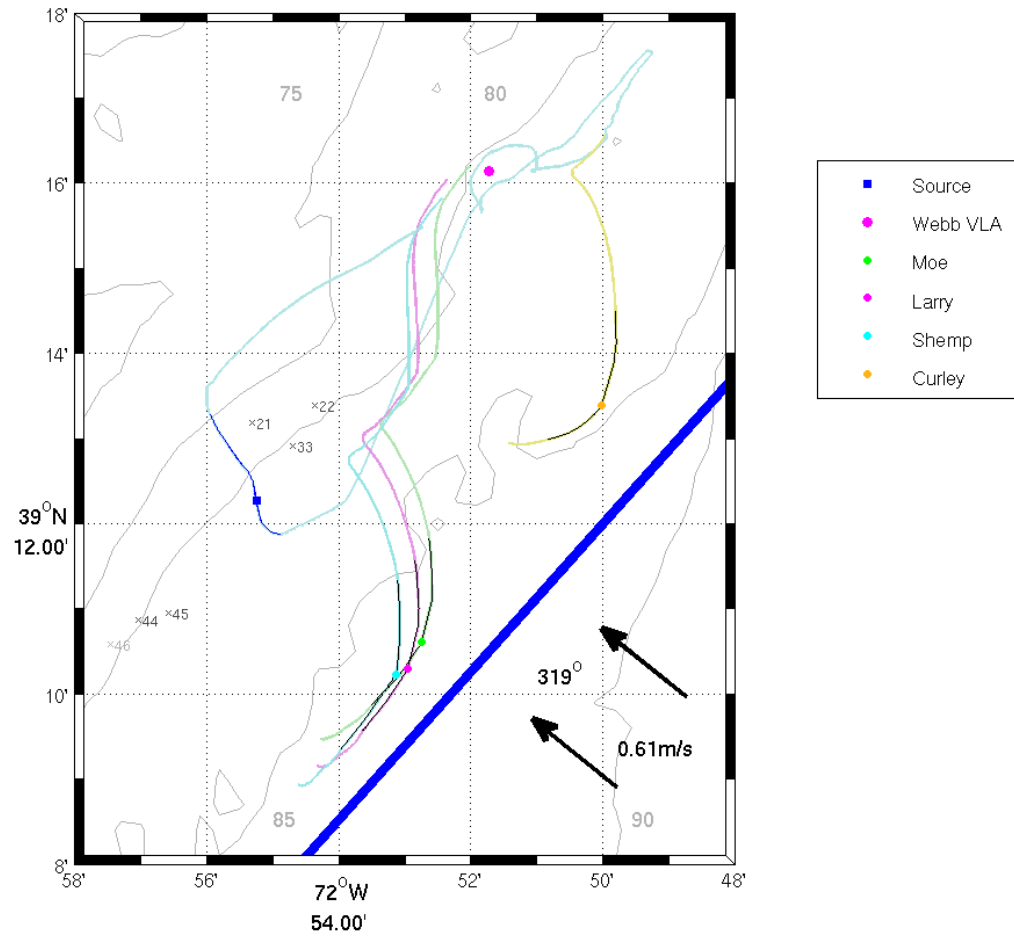


Figure 3: Tracks of source ship (R/V Oceanus) and 4 drifting buoys (Moe, Larry, Shemp, Curley) during SW06/MOMAX IV. The thick blue line depicts an internal wave with a speed of 0.61 m/s and a direction of 319 degrees as measured by temperature sensors at x21, x22, x33, x44, and x45. Also shown are the Webb VLA and 3 source moorings (x44, x45, and x46) in the experimental area.

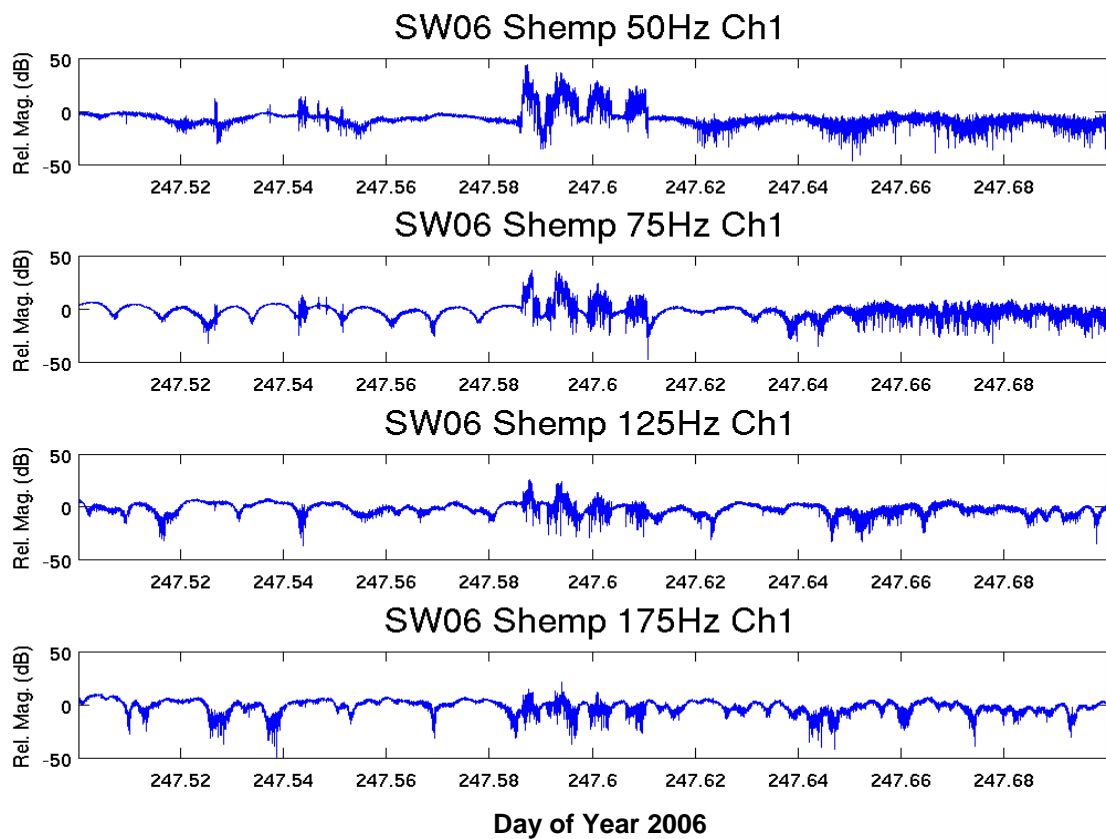


Figure 4: *Fluctuations in acoustic pressure magnitude measured at upper hydrophone on Shemp buoy during passage of internal wave on approximately day 247.6 at 4 frequencies.*

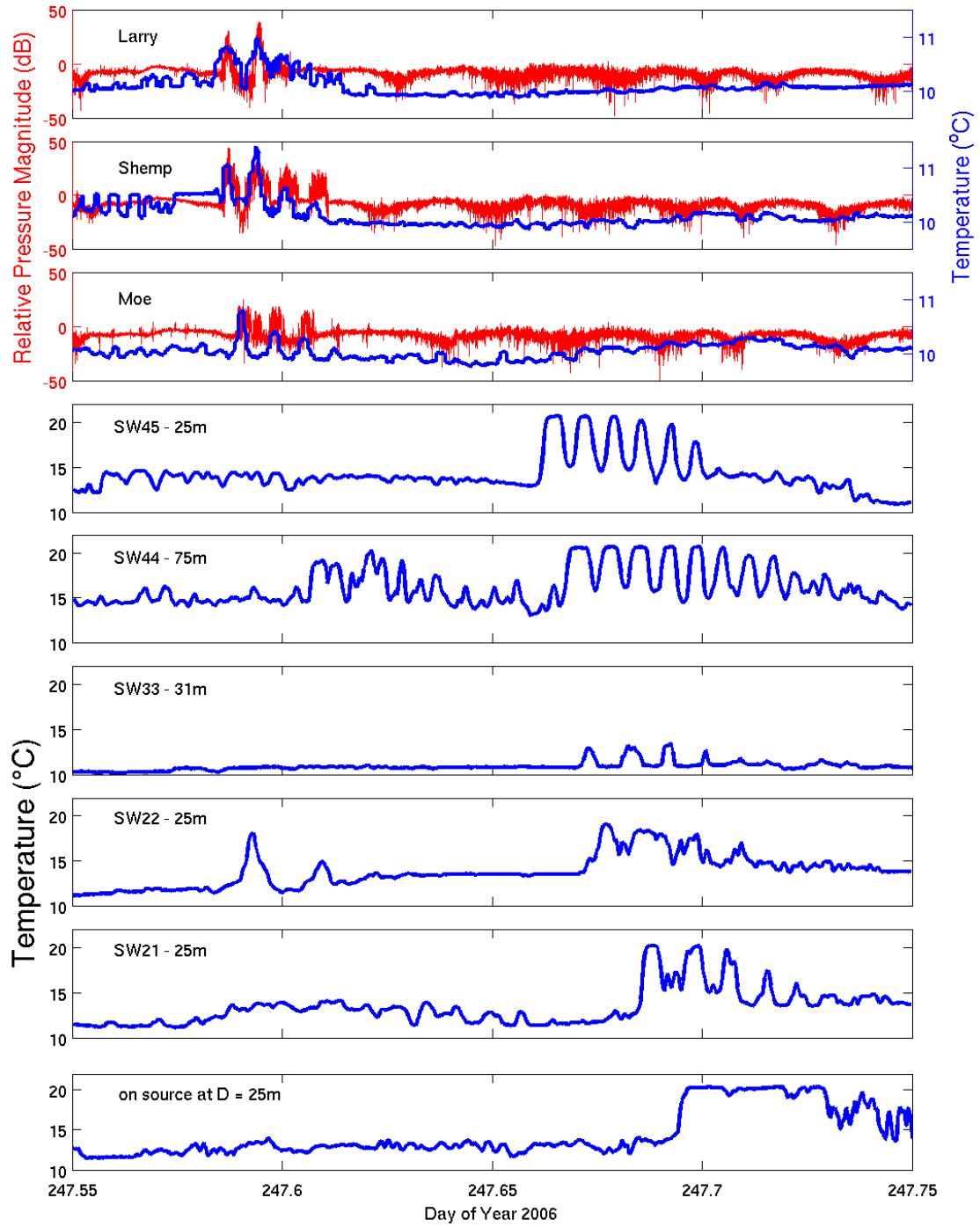


Figure 5: Temperature records (in blue) at various sensors in the experimental area indicating onshore progression of the internal wave. Also shown are the acoustic records (in red) which mimic the temperature records at 3 MOMAX buoys.

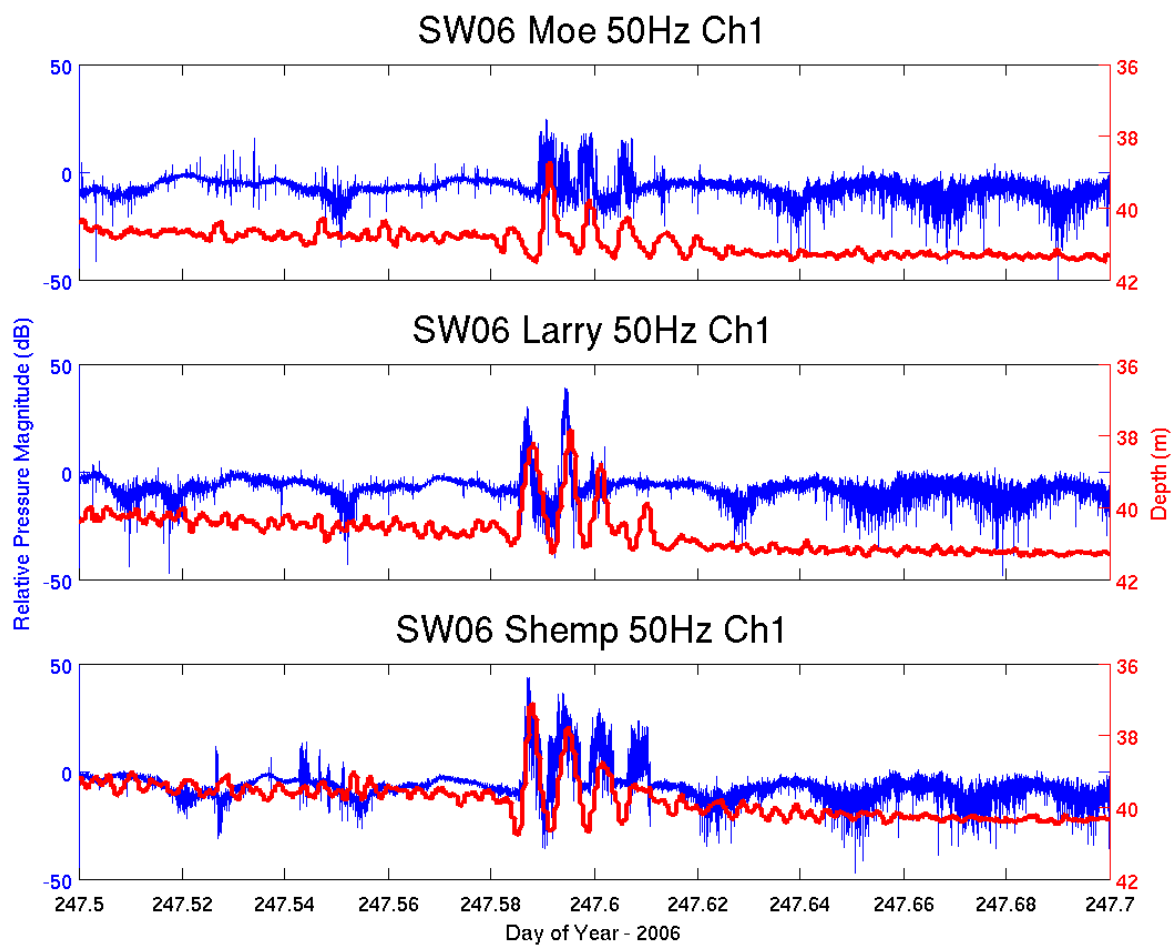


Figure 6: *Acoustic pressure magnitude fluctuations at the upper hydrophone (in blue) compared to hydrophone depth fluctuations (in red) at 3 MOMAX buoys.*

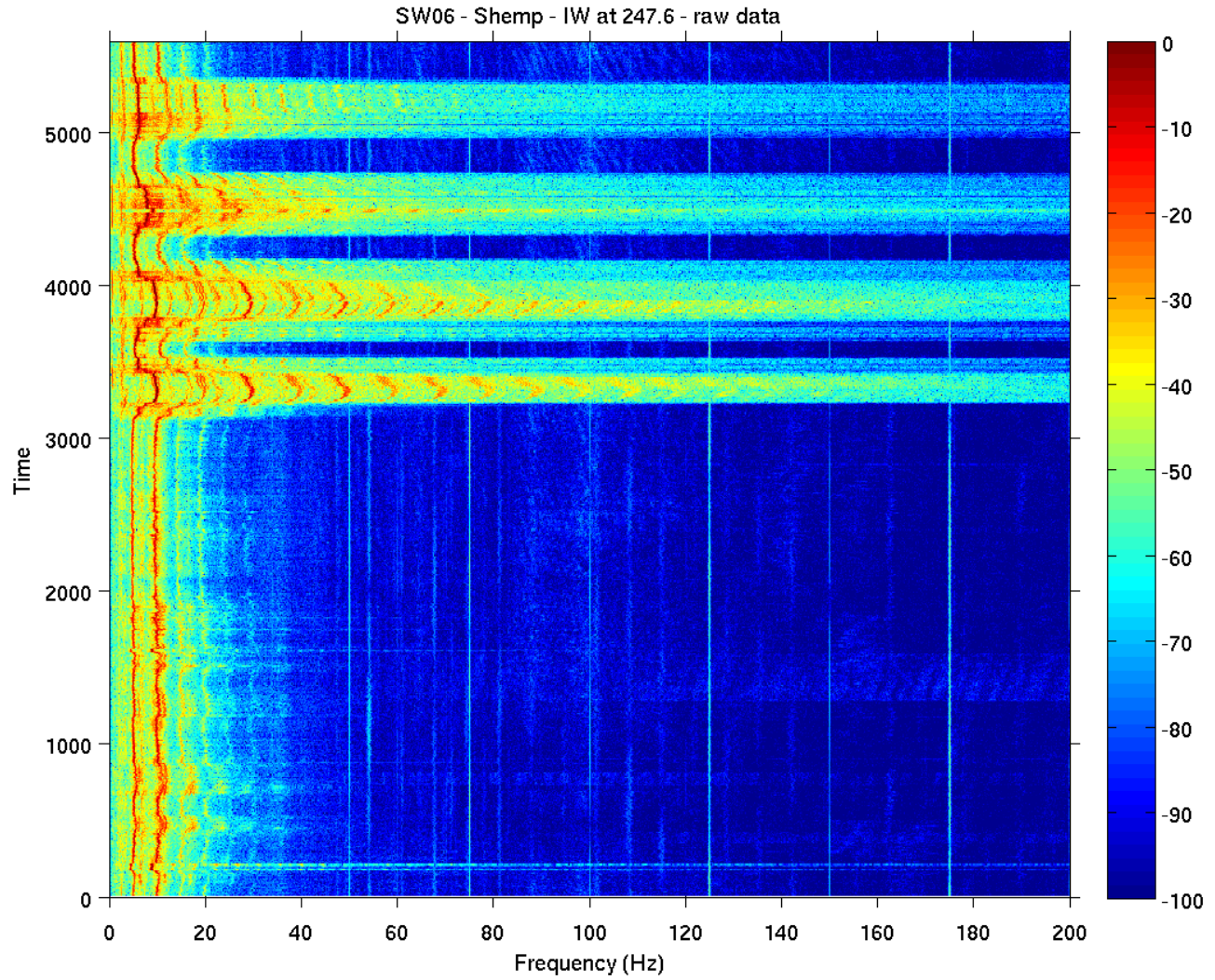


Figure 7: Acoustic spectrogram at Shemp (upper hydrophone) illustrating broadband smearing effect due to passage of internal wave.

REFERENCES

- G.V. Frisk, "A Review of Modal Inversion Methods for Inferring Geoacoustic Properties in Shallow Water," *invited paper in Full Field Inversion Methods in Ocean and Seismo-Acoustics*, edited by O. Diachok, A. Caiti, P. Gerstoft, and H. Schmidt (Kluwer, Netherlands, 1995).
- K. Ohta and G.V. Frisk, "Modal Evolution and Inversion for Seabed Geoacoustic Properties in Weakly Range-Dependent, Shallow-Water Waveguides," *IEEE J. Oceanic Engineering Special Issue on Shallow-Water Acoustics II*, **22**, 501-521 (1997).

J.A. Doust, G.V. Frisk, and H. Martell, "Determination of Distance Between a Moving Ship and Drifting Buoys to Centimeter-Level Accuracy at Sea Using L1 Phase Receivers and Differential Moving-Base Kinematic Processing," in *Proceedings of the Institute of Navigation GPS-98 Conference*, Nashville, Tennessee, 6 pages (15-18 September 1998).

J.A. Doust, G.V. Frisk, and H. Martell, "Using GPS at Sea to Determine the Range Between a Moving Ship and a Drifting Buoy to Centimeter-Level Accuracy," in *Proceedings of the Oceans '98 Conference*, Nice, France, 4 pages (28 September – 1 October 1998).

G.V. Frisk and K.M. Becker, "Modal Evolution and Inversion in Laterally Varying, Shallow-Water Waveguides," in *Proceedings of the International Conference on Acoustics, Noise and Vibration*, Montreal, Quebec, Canada, 5 pages (8-12 August 2000).

G.V. Frisk, K.M. Becker, and J.A. Doust, "Modal Mapping in Shallow Water Using Synthetic Aperture Horizontal Arrays," *invited paper* in *Proceedings of the Oceans 2000 MTS/IEEE Conference and Exhibition*, Providence, RI, 4 pages (11-14 September 2000).

G.V. Frisk, "The Relationship Between Low-Frequency Phase Rate and Source-Receiver Motion in Shallow Water: Theory and Experiment," *invited paper* in *Proceedings of the 17th International Congress on Acoustics*, Rome, Italy, 2 pages (2-7 September 2001).

L.L. Souza, G.V. Frisk, and K.M. Becker, "Application of the Gelfand-Levitan Method to the Estimation of the Seabed Sound Speed Profile," in *Proceedings of the V Encontro de Tecnologia em Acustica Submarina (V Underwater Acoustics Meeting)*, Rio de Janeiro, Brazil, 6 pages (21-23 November 2001).

G.V. Frisk, "Underwater Sound," *invited paper* in McGraw-Hill Yearbook of Science and Technology 2002, edited by M.D. Licker, 403-406 (McGraw-Hill, New York, 2001).

K.M. Becker and G.V. Frisk, "A Study on the Effects of Sound Speed Fluctuations Due to Internal Waves in Shallow Water on Horizontal Wavenumber Estimation," in *Proceedings of the Conference on the Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance (Lerici, Italy, 16-20 September 2002)*, edited by N.G. Pace and F.B. Jensen, 385-392 (Kluwer, Netherlands, 2002).

K.M. Becker, S.D. Rajan, and G.V. Frisk, "Results From the Geoacoustic Inversion Techniques Workshop Using Modal Inverse Methods," *invited paper*, *IEEE J. Oceanic Engineering Special Issue on Geoacoustic Inversion in Range-Dependent Shallow-Water Environments*, **28**, 331-341 (2003).

L.L. Souza, "Inversion for Subbottom Sound Velocity Profiles in the Deep and Shallow Ocean," Ph.D. Thesis, MIT/WHOI Joint Program in Oceanography/Applied Ocean Science and Engineering, Cambridge, MA and Woods Hole, MA (2005).

K. Ohta, K. Okabe, I. Morishita, S. Ozaki, and G.V. Frisk, "Inversion for Seabed Geoacoustic Properties in Shallow Water Experiments," *Acoustical Science and Technology (published by Acoustical Society of Japan)* **26**, 326-337 (1 July 2005).

K.M. Becker and G.V. Frisk, "Evaluation of an Autoregressive Spectral Estimator for Modal Wavenumber Estimation in Range-Dependent Shallow-Water Waveguides," *J. Acoust. Soc. Am.* **120**, 1423-1434 (2006).

T.L. Poole, "Geoacoustic Inversion by Mode Amplitude Perturbation," Ph.D. Thesis, MIT/WHOI Joint Program in Oceanography/Applied Ocean Science and Engineering, Cambridge, MA and Woods Hole, MA (February 2007).

PUBLICATIONS

K.M. Becker and G.V. Frisk, "The Impact of Water Column Variability on Horizontal Wavenumber Estimation and Mode Based Geoacoustic Inversion Results," *J. Acoust. Soc. Am.* **123**, 658-666 (2008) [published, refereed].

T.L. Poole, G.V. Frisk, J.F. Lynch, and A.D. Pierce, "Geoacoustic Inversion by Mode Amplitude Perturbation," *J. Acoust. Soc. Am.* **123**, 667-678 (2008) [published, refereed].

S.D. Rajan, G.V. Frisk, K.M. Becker, J.F. Lynch, G. Potty, and J.H. Miller, "Modal Inverse Techniques for Inferring Geoacoustic Properties in Shallow Water," Chap. 7, pp. 165-234, in A. Tolstoy (Ed.), *Important Elements in: Geoacoustic Inversion, Signal Processing, and Reverberation in Underwater Acoustics 2008* (Research Signpost, Kerala, India, 2008) [published].

K. Ohta, K. Okabe, I. Morishita, G.V. Frisk, and A. Turgut, "Modal Inversion Analysis for Geoacoustic Properties of the New Jersey Continental Shelf in the SWAT Experiments," to be published in *IEEE J. Oceanic Engineering* (2008) [accepted, refereed].

HONORS/AWARDS/PRIZES

G.V. Frisk, Vice President of the Acoustical Society of America.